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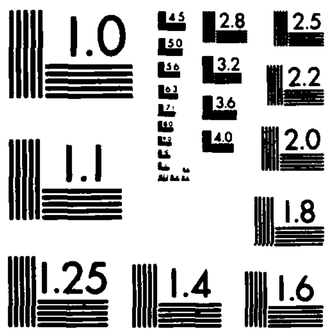

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Prediction of Slant Wind Shear With an Offset Tower Observation System

H. ALBERT BROWN

23 November 1983

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Analysis of remote tower measurements of wind speed collected at the AFGL Weather Test Facility at Otis AFB, Massachusetts, demonstrated the accuracy of an offset tower system to predict the Slant Wind Shear (SWS) over a runway. The study of wind shear has been one of a continuing program of field experiments conducted to develop and improve automation of weather observation and short-range prediction capabilities to meet future Air Force requirements.

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The objective was to evaluate the relative effectiveness of two statistically-based approaches (extrapolation and screening-regression-determined equations) using offset tower data in predicting SWS speed for intervals of 0, 5, 10, 15, 30 and 60 min at two levels of severity. A surface-based runway wind observation system was used as a comparative measure.

A variety of evaluation criteria were used to evaluate the techniques. The critical success index (CSI), modified to allow a higher rate of false alarms in predicting life threatening situations, showed that the screening regression technique achieved a higher, more nearly uniform, score over the full range of forecasts than the extrapolation technique at the low threshold of SWS intensity. At the higher threshold of SWS intensity, however, the extrapolation technique showed that the CSI's achieved by a 15 m and 30 m tower system were nearly equal and were better than the screening regression tests at time zero. For SWS forecasts of 5 min or greater, though, the screening regression technique was superior. Intercomparison of the several screening regression tests showed that the multiple 30 m tower system produced a higher CSI at time zero but that the surface based system gave higher CSI's for forecasts of 5 to 60 minutes.

Preface

The efforts of Mr. James H. Willand and Mrs. Joan Ward, Systems and Applied Sciences Corporation, in the formulation of the processing and prediction programs are most gratefully acknowledged. Many other individuals aided in this program—in particular, Mr. Leo Jacobs and Mr. Ralph Hoar of AFGL and Mr. Clyde Lawrance SASC, made a significant contribution in the maintenance, calibration, and operation of the sensors at the Otis Weather Test Facility. In addition, the author is most grateful to Mr. Donald Chisholm and Dr. Stuart Muench for many valuable discussions concerning the study, and also for their helpful comments on the paper itself. The author also wishes to acknowledge the kind assistance of Ms. Betty Blanchard in typing the manuscript.

Contents

Illustrations

Tables

Prediction of Slant Wind Shear With an Offset Tower Observation System

1. INTRODUCTION

Our lack of knowledge of the wind distribution in the lowest layers of the atmosphere surrounding an airport can present a practical and extremely important problem to aircraft operations. Fortunately, most of the time these winds represent no hazard to aircraft. Occasionally, however, wind shears occur that threaten the safety of the aircraft during takeoff or landing.

Schwarz[1] reports that in a survey of aircraft accidents, unfavorable winds ranked third in importance during the landing phase and ranked first in accidents occurring during takeoff. More recently, Frost[2] cited investigations of 25 commercial and 5 USAF accidents which showed that wind shear, either through speed or direction changes, was responsible in each case. The concern of the Air Weather Service (AWS) regarding wind shear was expressed by Forsyth[3] and is more formally addressed to AFGL through Geophysical Requirement 3-76, Short Range Terminal Forecast Techniques. It has also been documented through MAC ROC 501-76

(Received for publication 18 November 1983)

1. Schwarz, U. (1981) Aeronautical user requirements for meteorological information, Proceedings of 1st International Conference on Aviation Weather Systems, pp. 1-5.
2. Frost, W. (1983) Flight in Low-Level Wind Shear, NASA Contractor Report 3678.
3. Forsyth, M.D., Jr. (1981) Air Weather Service support to Air Force and Army aviation - present and future, Proceedings of 1st International Conference on Aviation Weather Systems, pp. 37-39.

which cites the AWS need for a low-altitude wind-warning system (LAWWS). Added emphasis on the need for action was a recent report[4] in which the National Transportation Safety Board recommended that the Federal Aviation Administration improve its airport weather and wind shear alert systems. This followed an investigation which determined that wind shear was the probable cause of an airline crash during takeoff from the New Orleans Airport on 9 July 1982.

A previous paper by Brown[5] postulated that neither the vertical wind shear nor horizontal wind shear alone represents the wind shear of most importance to the pilot. The aircraft, in taking off or landing, follows a sloping trajectory, therefore it encounters winds separated in height by hundreds of meters and in horizontal distance by thousands of meters. Thus, the wind shears measured along a vertical axis alone, for example, by a tower or an acoustic doppler sounder, or along a horizontal axis, by a surface network of wind sets, may give an erroneous representation of the actual wind shear the aircraft will encounter on its slanting approach or takeoff. The term Slant Wind Shear (SWS) was proposed to represent this operationally important wind measurement in a manner analogous to the term Slant Visual Range, which describes the visual range a pilot has along the approach path at decision height.

This SWS could best be specified by a measurement of the winds at the touchdown or takeoff point and by wind towers of ever increasing height along the approach or takeoff path. Such a solution is obviously impossible. Thus Brown,[5] in a preliminary analysis, studied the ability of surface wind sets along the runway near touchdown or takeoff points together with wind towers offset from the center line of the runway to specify the true SWS along the aircraft trajectory.

This report represents a continuation of the study of offset towers. The objective is to evaluate the relative effectiveness of two statistically-based approaches (extrapolation and screening-regression-determined equations) using offset tower data in predicting SWS for intervals of 0, 5, 10, 15, 30 and 60 minutes. A surface-based runway wind observation approach will be used as a comparative measure.

2. TEST FACILITY AND DATA BASES

The study of wind shear has been one of a continuing program of field experiments conducted at the Air Force Geophysics Laboratory (AFGL) Weather Test Facility (WTF) at Otis Air Force Base, Massachusetts. The primary aim of the

4. Kozicharow, E. (1983) NTSB cites wind shear in New Orleans accident, Article printed in Aviation Week & Space Technology, March 28, 1983, p. 32.

5. Brown, H.A. (1982) Analysis and Specification of Slant Wind Shear, AFGL-TR-82-0366, AD A125883.

program was to develop and improve the automation of the observation and short-range forecasting weather support function[6] to meet future Air Force requirements.

Figure 1 shows the configuration of the tower and ground site. The imaginary runway lies parallel to the A-X axis. Towers P and Q (30 m in height) are the offset towers located at a proper distance (500 m) to conform to Air Force Regulation, AFR 86-14. More detailed discussions of the instruments and towers are given in Brown.[5] Wind measurements were obtained from Climatronics wind sets mounted on three towers (A, P and Q) and at a ground location (X). Wind data was also used from one Gill wind set mounted at the 60 m level of Tower A. Profiles of temperature were obtained from EG&G Temperature-Dewpoint sensors.

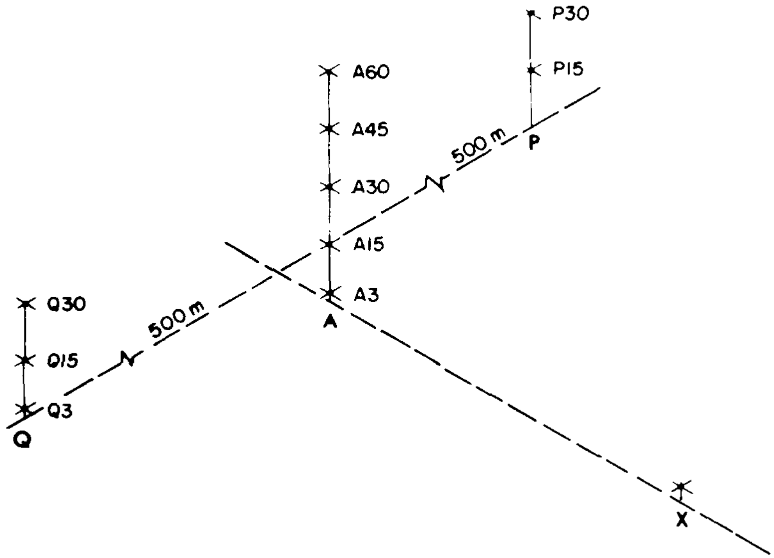

Figure 1. Configuration of Instrumented Towers and Ground Site at the AFGL Weather Test Facility, Otis AFB

The primary data collection system at the WTF during the period of this test was an automatic data logger which collected wind direction and speed information at the rate of ten observations per min (temperature at the rate of 5). These data were placed on magnetic tape and subsequently processed to produce 1-min averages of wind speed, wind direction, temperature, SWS, and temperature difference.

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6. Chisholm, D.A., Lynch, R.H., Weyman, Capt. J.C., and Geisler, Capt. E.B. (1980) A Demonstration Test of the Modular Automated Weather System (MAWS) AFGL-TR-80-0087, AD A087070.

The WTF data for the period 28 March to 4 May 1981 were processed, calibrated, and evaluated for SWS conditions. Details of the SWS occurrences and associations with other variables were given in the previous report.[5] The period could roughly divided into two regimes. The first regime consisted of higher frequency of gusty winds, as reported by FAA observers at Otis AFB, and also frequent frontal passages. The second regime, on the other hand, had significantly fewer hours of gusty wind and half as many frontal passages. The entire data set, consisting of 45,000 min of data, was treated as the dependent set in the derivation of the specification and prediction equations.

An independent data set, consisting of 4200 min of data occurring between 16 - 19 March 1981, was selected for its high frequency of SWS occurrences. Another factor in choosing the independent data set during the same spring season was the reasoning that seasonal variations could be significant. Table 1 shows the frequency of occurrence and percentage frequency of the 1-min average SWS value calculated between the 60-m level of the A tower and the 3-m level at site X for the dependent and independent data sample. The wind shear intensity criteria given by Badner[7] have been used in this study. The increased frequency of occurrence of SWS in the moderate and higher categories of the independent set is apparent. This increase in SWS frequencies is felt to be strictly a function of the time length of the data base. Given a longer data base, the frequencies of occurrence would shift to the lighter values of SWS.

3. EVALUATION CRITERIA

A severe weather predictor or procedure should be evaluated on its ability to detect or warn of a severe event. This ability must be balanced between the need to avoid missing the threat of severe events and at the same time to avoid the opposite extreme of giving too many false alarms. A Critical Success Index (CSI) was introduced[8] as an objective evaluator of the merit of techniques for predicting severe weather. The CSI takes into consideration both classes of error, missed threats and false alarms.

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7. Badner, J. (1979) Low-Level Wind Shear: A Critical Review, NOAA Technical Memorandum NWS FCST-23.

8. Donaldson, R.J., Jr., Dyer, R.M., and Kraus, M.J. (1975) Operational Benefits of Meteorological Doppler Radar, AFCRL-TR-75-0103, AD A010434.

Table 1. Frequencies of Occurrence of SWS Speeds for Dependent and Independent Data Set

SWS Intensity (m sec^{-1}/60 min)	Dependent Data		Independent Data	
	Minutes	Frequency %	Minutes	Frequency %
Light 0 - 3.9	25,544	57	1,831	43
Moderate 4 - 7.9	18,558	42	2,241	53
Strong 8 - 11.9	501	1	178	4
Severe > 12	2	*	4	
Total Minutes	44,605		4,254	

* < .01%

An example of the 2 × 2 contingency table constructed for a test is shown in Figure 2. The data have been categorized by a SWS speed threshold of 4 m sec^{-1}/60 m. This threshold separates the light SWS speeds from those moderate or greater (see Table 1). The matrix squares are labeled x, y, z, and w. The sum of x + y gives the total number of observed SWS speeds which are moderate or greater in strength. The sum w + z represents the total observations of light SWS speed. The quantities x and w represent correct forecasts while y indicates missed threats and z indicates false alarms. Equations for the probability of detection (POD), false alarm ratio (FAR) and critical success (CSI) are shown below the figure. An additional calculation, a weighted CSI*, is also shown. It allows for an increased value of CSI in the case where a higher false alarm rate is acceptable due to the severity of the phenomena forecast. Obviously, an aircraft threatening wind shear condition would be most severe and a modulus of z/10 was chosen for this calculation.

SWS SPEEDS SPECIFIED

SWS SPEEDS OBSERVED	< 4	≥ 4 msec^{-1}/60 m
< 4	24770 W	1548 Z
≥ 4 msec^{-1}/60 m	1225 Y	17073 X

$$POD = \left(\frac{X}{X + Y}\right) \times 100 = 93 \text{ percent}$$

$$FAR = \left(\frac{Z}{X + Z}\right) \times 100 = 8 \text{ percent}$$

$$CSI = \left(\frac{X}{X + Y + Z}\right) \times 100 = 86 \text{ percent}$$

$$CSI' = \left(\frac{X}{X + Y + Z/10}\right) \times 100 = 93 \text{ percent}$$

Figure 2. Contingency Table Illustrating the Method of Computing the SWS Speed Verification Scores. Probability of Detection (POD), False Alarm Ratio (FAR), Critical Success Index (CSI), and Modified Critical Success Index (CSI′)

4. SLANT WIND SHEAR SPECIFICATION

The ability of offset tower-surface winds to specify the SWS direction and speed over the landing or takeoff zone of an air base was previously examined.[5] Three basic tests were performed to determine how well the SWS (between a 60-m tower and a surface site) along a runway would be specified by an offset tower system. The first consisted of computing the SWS from offset 30-m towers and surface sites. The second utilized SWS winds computed between 15-m offset tower and a surface site. The third test, representing the surrent capability at most air bases, used SWS computations obtained from surface sites only.

Table 2 gives a summary of the three tests. One principal conclusion was that the winds from 15-m offset towers were essentially equivalent to those from 30-m towers in specifying SWS in two categories. The two categories included SWS values of moderate intensity or greater (4 m sec^{-1}/60 m) and values of strong SWS or greater (8 m sec^{-1}/60 m). SWS directions were also specified equally well by the 15-m towers. The other conclusion drawn from the study was that the surface-based wind system was significantly less effective in specifying SWS speed or direction.

Table 2. Statistical Results of 30-m, 15-m, and Surface Wind Systems as Specifiers of SWS Speed and Direction

a. SWS Speed			
Statistic	30 m	15 m	Surface
Correlation Coefficient	0.62	0.57	0.25
rmse (m sec^{-1})	1.46	1.65	2.66
Threshold (4 m sec^{-1}/60 m)			
POD	76	78	4
FAR	18	25	10
CSI	65	62	4
CSI* (Z/10)	75	76	4
Threshold (8 m sec^{-1}/60 m)			
POD	54	52	0
FAR	83	82	0
CSI	15	15	0
CSI* (Z/10)	43	42	0

b. SWS Direction			
Statistic	30 m	15 m	Surface
Correlation Coefficient	0.90	0.90	0.62
rmse (degrees)	41	45	91
Total Percent Correct, All Directions	84	78	49

5. PREDICTION TECHNIQUES

Two basic techniques were used to determine the relationships between the variety of predictors of SWS at the Otis WTF and the predictand of SWS over the landing or approach zone of the runway at intervals of 0, 5, 10, 15, 30 and 60 min after the initial observation. The techniques are extrapolation and stepwise screening regression. The product (predictand) of both techniques is the most probable SWS.

5.1 Extrapolation

For the purpose of this study, the true SWS (predictand) was calculated as the shear between the 1-min average vector wind observed at the 60-m level of tower A and the 3-m level of site X (see Figure 1).

$$\Delta W = W_{A60} - W_x .$$

The objective of the extrapolation technique was to determine how well the predictand SWS could be forecast from various combinations of wind shear obtained from the offset towers P and Q and the surface site X.

Test 1 SWS calculated between 30-m winds measured at offset towers P and Q, then extrapolated to 60-m in height and surface winds measured at site X

$$\Delta W_1 = K_1 W_{P30} - W_x$$

$$\Delta W_2 = K_1 W_{Q30} - W_x$$

Test 2 SWS calculated between 15-m winds measured at offset towers P and Q, then extrapolated to 60-m in height and surface winds measured at site X

$$\Delta W_3 = K_2 W_{P15} - W_x$$

$$\Delta W_4 = K_2 W_{Q15} - W_x$$

Test 3 SWS calculated between surface winds at towers A and Q and at site X. No extrapolation to a greater height was made as this represents the capability of current surface wind measurements.

$$\Delta W_5 = W_{A3} - W_x \quad (\sim 300\text{-m surface separation})$$

$$\Delta W_6 = W_{Q3} - W_x \quad (\sim 500\text{-m surface separation}) .$$

The extrapolation coefficients K_1 and K_2 were obtained as a product of the previous study.[5] Ratios of winds between 30 and 60 m and between 15 and 60 m were calculated using wind averaged over one hour. Data were further stratified based on two wind speed regimes at the 15- and 30-m levels. Figures illustrating the time variation of K and the effect of high and low wind speed regimes can be seen in the previous report.[5] The extrapolation technique derives not only a forecast of the SWS speed but also the SWS direction. SWS direction specifications by offset towers were also covered in the previous paper and proved very reliable. Forecasts of SWS direction by the extrapolation method will not be covered in this report because the screening regression procedure could not be structured to yield SWS direction predictions.

5.2 Screening Regression

Screening regression is a statistically-based procedure which has proved to be a valuable tool in many fields in addition to meteorology.[9] For a given predictand, it selects a subset of predictors in a step-wise manner and then forms a multiple regression equation relating the selected predictors to the predictand. The choice of possible regression predictors, from the variety of instrument combinations available at the Otis WTF, was made to parallel, as nearly as possible, the selection of the extrapolation predictors.

Seven tests were chosen for screening regression estimation. A summary of the tests is shown in Table 3. Test 1 consists of wind (V) and wind shear (ΔV) predictors from the two 30-m towers (P and Q) and the surface site (X), temperature lapse rate (items 16 and 17) and measures of time of day (items 18 and 19). Tests 2 and 3 limit data to a single 30-m tower (P or Q) together with a temperature profile. Test 4 was selected to have two 15-m towers and accompanying temperature profile. Tests 5 and 6 are given a single 15-m tower and corresponding 15-m temperature profile. Finally Test 7 is constrained to surface-based winds with no temperature profile available.

SWS speed forecasts were enhanced using a technique referred to by Carter and Schwartz.[10] An examination of the forecast SWS frequencies prior to enhancement revealed that both low and high values of SWS were diminished due to the screening regression technique. Thus, too few forecasts of high SWS were produced. An enhancement (or inflation) equation was used as follows:

$$\Delta V_E = \frac{\Delta V - \overline{\Delta V}}{r} + \Delta V$$

where ΔV is the original forecast of the SWS speed, $\overline{\Delta V}$ is the mean value for the SWS speed predictand from the developmental data sample, r is the multiple correlation coefficient of the SWS speed predictand with the predictors, and ΔV_E is the enhanced forecast of SWS speed.

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9. Miller, R.G., Editor (1977) Selected Topics in Statistical Meteorology, AWS-TR-77-273, Chapter 3, 7 pp.

10. Carter, G.M., and Schwartz, B.E. (1982) The use of model output statistics for predicting surface wind, National Weather Service Technical Procedures Bulletin Series No. 216, 13 pp.

Table 3. Summary of Tests Used in Screening Regression Analysis. A circle marks the predictor offered in each test. Filled circles denote the subset of predictors selected by screening regression

	Test →	1	2	3	4	5	6	7
	Predictor ↓	All Data	P30	Q30	P15 Q15	P15	Q15	Q3
1	V (P30)	●	●					
2	V (Q30)	●		●				
3	V (P15)	○			●	●		
4	V (Q15)	○			●		●	
5	V (X3)	●						●
6	V (Q3)	○						●
7	ΔV (P30 - X3)	●	●					
8	ΔV (Q30 - X3)	●		●				
9	ΔV (P15 - X3)	○	●		●	●		
10	ΔV (Q15 - X3)	○		○	○		●	
11	ΔV (Q3 - X3)	○		●	○		●	○
12	ΔV (P30 - P15)	○	●					
13	ΔV (Q30 - Q15)	○		○				
14	ΔV (Q30 - Q3)	○		●				
15	ΔV (Q15 - Q3)	○			○		○	
16	ΔT (A30 - X3)	●	●	●				
17	ΔT (A15 - X3)	●			●	●	●	
18	Sine Time	●	●	●	●	●	●	●
19	Cos Time	●	●	○	○	●	○	●

6. EVALUATION OF PREDICTION TECHNIQUES

Forecasts of SWS speed by the two forecasting techniques, extrapolation and screening regression, were verified separately on the independent data samples for each individual test and for each of several forecast intervals. Verification was performed on data which had been divided into two categories. In the first test,

2 × 2 contingency tables were constructed to separate data between light and moderate or greater SWS (a separation threshold of 4 m sec^{-1}/60 m). In the second test, tables were constructed to separate data between light plus moderate and strong or greater (a separation threshold of 8 m sec^{-1}/60 m). In addition to the verification measures referred to in Section 3, correlation coefficients and root-mean square errors were also calculated.

6.1 Correlations

Tables 4a and 5a show the correlations for the extrapolation and screening regression techniques respectively. The extrapolation results, Table 4a, are similar to those obtained in the earlier report[5] for the zero time lag. The 15-m correlations are comparable to those at 30 m. Of interest is the fairly sharp decrease in correlation between 0 and 5 min and the leveling off that occurs between 5 and 60 min, reflecting the short-lived nature of wind fluctuations. The correlation of the surface systems, tests 5 and 6, are low for all time periods.

The correlations for the screening regression technique are, overall, very even, with less drop in magnitude between 0 and 5 min than the extrapolation technique. Test 1, which incorporated all data, has a slightly higher correlation between predicted and observed SWS speeds at time zero but for all other times and tests the results are essentially equal. They also exceed the extrapolation correlation coefficients at all times except time zero.

6.2 Root-Mean-Square Errors

The rms errors in the extrapolation technique are shown in Table 4b. The RMSE's for Tests 1 and 2 (30-m tower winds) are slightly lower than Tests 3 and 4 (15-m tower winds) at zero time lag. From 5 to 60 min forecasts, however, errors of the 15-m and 30-m tower tests are essentially equal. The surface system, Tests 5 and 6, have the largest rms errors throughout.

The rms errors in the screening regression technique, Table 5b, are lower overall, than those in the extrapolation tests. Also, very little variation is seen among the various tests of screening regression. The surface system, Test 7, with a minimum of data and restricted to surface data alone is almost equivalent to Test 1, characterized by a maximum of data, at all times except at time zero.

6.3 Probability of Detection (POD)

Summaries of POD for two thresholds of SWS obtained from the extrapolation tests are shown in Tables 6a and 6b. A few features become immediately apparent. Test 2, which uses data from the 30-m tower at Q, departs significantly from other 30-m tests (1) and also from the 15-m tests (3 and 4). Examination of the original

Q30 contingency tables reveals an unusually high number of missed threats in both threshold categories. Further examination showed that the average wind speed at Q30 was approximately 0.5 m sec^{-1} lower than the average speed at P30. This would shift the forecast frequency distribution to lower values and result in lower POD's.

Table 4. Values of (a) Correlation Coefficient and (b) Root-Mean-Square Error Resulting From the Extrapolation Technique for Specifying and Predicting SWS

a. Correlation Coefficient

		Forecast (minutes)					
	Test	0	5	10	15	30	60
1	K_1 P30 - X	0.59	0.37	0.37	0.38	0.35	0.33
2	K_1 Q30 - X	0.53	0.32	0.33	0.34	0.34	0.31
3	K_2 P15 - X	0.56	0.36	0.35	0.36	0.34	0.32
4	K_2 Q15 - X	0.54	0.32	0.34	0.36	0.34	0.32
5	A3 - X	0.29	0.21	0.24	0.23	0.22	0.23
6	Q3 - X	0.23	0.20	0.20	0.20	0.17	0.18

b. Root-Mean-Square Error (m sec^{-1})

		Forecast (minutes)					
	Test	0	5	10	15	30	60
1	K_1 P30 - X	1.94	2.37	2.37	2.35	2.40	2.44
2	K_1 Q30 - X	1.98	2.37	2.35	2.33	2.35	2.39
3	K_2 P15 - X	2.01	2.41	2.42	2.40	2.44	2.48
4	K_2 Q15 - X	2.02	2.43	2.41	2.37	2.40	2.44
5	A3 - X	3.22	3.28	3.26	3.26	3.28	3.27
6	Q3 - X	3.34	3.37	3.36	3.37	3.38	3.38

Table 5. Values of (a) Correlation Coefficient and (b) Root-Mean-Square Error Resulting From the Screening Regression Technique for Specifying and Predicting SWS

a. Correlation Coefficient

	Test	Forecast (minutes)					
		0	5	10	15	30	60
1	P30, Q30	0.65	0.55	0.54	0.55	0.53	0.51
2	P30	0.59	0.53	0.53	0.53	0.50	0.48
3	Q30	0.56	0.54	0.43	0.53	0.52	0.50
4	P15, Q15	0.57	0.54	0.54	0.54	0.51	0.50
5	P15	0.55	0.53	0.52	0.53	0.49	0.49
6	Q15	0.54	0.53	0.52	0.52	0.50	0.49
7	Surface	0.55	0.54	0.53	0.53	0.51	0.50

b. Root-Mean-Square Error (m sec^{-1})

	Test	Forecast (minutes)					
		0	5	10	15	30	60
1	P30, Q30	1.62	1.86	1.86	1.86	1.89	1.94
2	P30	1.75	1.86	1.87	1.85	1.89	1.93
3	Q30	1.82	1.88	1.89	1.88	1.91	1.95
4	P15, Q15	1.81	1.83	1.84	1.83	1.88	1.90
5	P15	1.83	1.84	1.86	1.86	1.91	1.93
6	Q15	1.88	1.90	1.89	1.89	1.93	1.97
7	Surface	1.87	1.97	1.99	1.99	2.02	2.06

Other features of note are the near-equivalence of the 15-m tests POD's to the 30-m POD's. The POD does not drop off sharply in the first threshold test but does decrease markedly in the second threshold test between 0 and 5 min lag implying a lack of persistence of shears above the second level. The surface system, tests 5 and 6, are ineffective in predicting SWS at either threshold.

Table 6. Values of Probability of Detection (POD) for the Prediction of SWS Speed Using the Extrapolation Technique. POD values are percentages. Thresholds are for (a) 4 m sec^{-1}/60 m and (b) 8 m sec^{-1}/60 m

a. SWS Speed Threshold (4 m sec^{-1}/60 m)

	Test	(Forecast (minutes)					
		0	5	10	15	30	60
1	K_1 P30 - X	84	77	77	77	76	75
2	K_1 Q30 - X	72	63	63	64	63	62
3	K_2 P15 - X	78	71	71	71	70	69
4	K_2 Q15 - X	77	69	69	70	69	70
5	A3 - X	7	7	8	8	8	8
6	Q3 - X	7	8	7	8	7	8

b. SWS Speed Threshold (8 m sec^{-1}/60 m)

	Test	(Forecast (minutes)					
		0	5	10	15	30	60
1	K_1 P30 - X	52	27	31	34	36	29
2	K_1 Q30 - X	32	22	18	22	24	21
3	K_2 P15 - X	49	28	31	37	32	29
4	K_2 Q15 - X	41	26	25	26	34	26
5	A3 - X	1	0	1	0	0	0
6	Q3 - X	1	0	1	0	0	0

The screening regression tests, Tables 7a and 7b, show a remarkable consistency in time and with various tests at both thresholds. However, the first threshold has uniformly high values of POD, superior to those obtained by extrapolation, while the second threshold exhibits uniformly lower values of POD, and somewhat less than the extrapolation tests of 30-m and 15-m at time zero. At later times the screening regression tests produced POD's equivalent to the extrapolation tests.

Table 7. Values of Probability of Detection (POD) for the Prediction of SWS Speed Using the Screening Regression Technique. POD values are percentages. Thresholds are for (a) 4 m sec^{-1}/60 m and (b) 8 m sec^{-1}/60 m

a. SWS Speed Threshold (4 m sec^{-1}/60 m)

	Test	Forecast (minutes)					
		0	5	10	15	30	60
1	P30, Q30	87	87	87	86	86	85
2	P30	84	86	84	85	84	83
3	Q30	85	85	85	85	84	85
4	P15, Q15	84	84	84	85	83	83
5	P15	82	83	83	83	82	82
6	Q15	84	84	84	84	83	83
7	Surface	89	90	90	90	90	90

b. SWS Speed Threshold (8 m sec^{-1}/60 m)

	Test	Forecast (minutes)					
		0	5	10	15	30	60
1	P30, Q30	43	33	29	38	36	38
2	P30	37	28	27	30	28	28
3	Q30	26	31	28	36	37	38
4	P15, Q15	33	26	22	31	28	26
5	P15	28	24	22	32	26	28
6	Q15	26	30	26	33	29	32
7	Surface	36	48	42	45	45	45

6.4 False Alarm Ratio (FAR)

Summaries of FAR for two thresholds of SWS obtained from both extrapolation and screening regression are shown in Tables 8a and 8b and Tables 9a and 9b respectively. For the extrapolation tests, values of FAR for the first threshold are consistent for time zero. At the 5-min forecasts, the FAR rate increases for all tests except the surface stations, Tests 5 and 6. Again there is essential equivalence of the 15-m and 30-m towers. A dramatic increase in FAR occurs for the

second threshold, Table 8b. It should be noted that the erratic behavior of FAR in Tests 5 and 6 is due to the low frequency of forecasts of SWS greater than the threshold by these tests. Re-examination of Table 6b for these tests shows the low POD and reaffirms that in the few cases that high SWS was forecast, it failed to verify.

Table 8. Values of False Alarm Ratio (FAR) for the Prediction of SWS Speed Using the Extrapolation Technique. FAR values are perventages. Thresholds are for (a) 4 m sec^{-1}/60 m and (b) 8 m sec^{-1}/60 m

a. SWS Speed Threshold (4 m sec^{-1}/60 m)

	Test	Forecast (minutes)					
		0	5	10	15	30	60
1	K_1 P30 - X	19	25	25	25	26	27
2	K_1 Q30 - X	15	25	24	23	24	25
3	K_2 P15 - X	18	25	25	25	26	26
4	K_2 Q15 - X	17	29	25	24	25	25
5	A3 - X	17	14	14	11	13	12
6	Q3 - X	13	12	16	10	13	10

b. SWS Speed Threshold (8 m sec^{-1}/60 m)

	Test	Forecast (minutes)					
		0	5	10	15	30	60
1	K_1 P30 - X	73	86	84	83	82	85
2	K_1 Q30 - X	70	80	83	79	79	80
3	K_2 P15 - X	74	85	84	81	83	84
4	K_2 Q15 - X	76	85	85	84	80	84
5	A3 - X	36	100	0	100	100	100
6	Q3 - X	0	100	50	100	100	100

Table 9. Values of False Alarm Ratio (FAR) for the Prediction of SWS Speed Using the Screening Regression Technique. FAR values are percentages. Thresholds are for (a) 4 m sec^{-1}/60 m and (b) 8 m sec^{-1}/60 m

a. SWS Speed Threshold (4 m sec^{-1}/60 m)							
		Forecast (minutes)					
	Test	0	5	10	15	30	60
1	P30, Q30	17	23	23	23	23	24
2	P30	19	22	23	23	23	24
3	Q30	20	23	23	24	24	24
4	P15, Q15	21	23	23	23	23	23
5	P15	21	23	23	23	24	24
6	Q15	22	23	24	24	24	24
7	Surface	23	26	26	27	27	27

b. SWS Speed Threshold (8 m sec^{-1}/60 m)							
		Forecast (minutes)					
	Test	0	5	10	15	30	60
1	P30, Q30	60	73	75	67	67	69
2	P30	66	70	69	64	67	65
3	Q30	74	70	73	66	67	67
4	P15, Q15	66	63	71	58	62	65
5	P15	69	67	71	62	66	65
6	Q15	73	70	73	67	70	71
7	Surface	74	73	77	75	75	76

The screening regression tests for the first threshold, Table 9a, produced remarkably low and consistent values of FAR. In the second threshold tests, however, a different picture is seen. Values of FAR have increased significantly, however, not as high as in the extrapolation tests.

6.5 Critical Success Index (CSI)

The critical success index (CSI) has been defined as the ratio of successful predictions of a critical event to the sum of the successful predictions plus the missed threats and the false alarms (see Figure 2). Examination of the results of the extrapolation tests, Table 10a, shows values of CSI ranging from the mid-sixties at time zero to the mid-fifties at the 60-min forecasts. The surface system, tests 5 and 6, consistent with the low values of POD seen in Table 6a, show low values of CSI. Table 10b shows a marked drop in the magnitude of CSI with the zero time lag falling the least. Values of CSI are quite comparable between the 15-m and 30-m tower while the surface systems, tests 5 and 6, are essentially zero.

Table 10. Values of Critical Success Index (CSI) for the Prediction of SWS Speed Using the Extrapolation Technique. CSI values are percentages. Thresholds are for (a) 4 m sec^{-1}/60 m and (b) 8 m sec^{-1}/60 m

a. SWS Speed Threshold (4 m sec^{-1}/60 m)

		Forecast (minutes)					
	Test	0	5	10	15	30	60
1	K_1 P30 - X	70	62	61	61	60	58
2	K_1 Q30 - X	64	51	53	54	52	52
3	K_2 P15 - X	67	57	58	57	56	56
4	K_2 Q15 - X	66	54	56	57	56	56
5	A3 - X	7	7	8	8	8	8
6	Q3 - X	7	7	7	7	7	7

b. SWS Speed Threshold (8 m sec^{-1}/60 m)

		Forecast (minutes)					
	Test	0	5	10	15	30	60
1	K_1 P30 - X	21	10	12	13	13	11
2	K_1 Q30 - X	18	12	10	12	13	11
3	K_2 P15 - X	20	11	12	15	12	11
4	K_2 Q15 - X	18	11	10	11	14	11
5	A3 - X	1	0	1	0	0	0
6	A3 - X	1	0	1	0	0	0

The screening regression tests, Table 11, show even more uniform results for all tests. No marked drop in CSI occurs between 0 and 5-min forecast for either threshold, Tables 11a and 11b. As a result the screening regression CSI's are equal to the extrapolation CSI's at time zero and at later times are higher than the corresponding values for the extrapolation tests.

Table 11. Values of Critical Success Index (CSI) for the Prediction of SWS Speed Using the Screening Regression Technique. CSI values are percentages. Thresholds are for (a) 4 m sec^{-1}/60 m and (b) 8 m sec^{-1}/60 m

a. SWS Speed Threshold (4 m sec^{-1}/60 m)

		Forecast (minutes)					
	Test	0	5	10	15	30	60
1	P30, Q30	74	69	69	69	68	67
2	P30	70	69	67	68	67	66
3	Q30	70	68	68	67	67	67
4	P15, Q15	68	68	68	68	66	66
5	P15	67	67	66	66	65	65
6	Q15	67	68	67	66	66	66
7	Surface	70	69	69	68	68	68

b. SWS Speed Threshold (8 m sec^{-1}/60 m)

		Forecast (minutes)					
	Test	0	5	10	15	30	60
1	P30, Q30	26	17	16	21	21	20
2	P30	22	17	17	20	18	18
3	Q30	15	18	16	21	21	21
4	P15, Q15	20	18	14	22	19	18
5	P15	17	16	14	21	17	18
6	Q15	15	18	15	20	17	18
7	Surface	18	21	18	19	19	18

6.6 Modified Critical Success Index (CSI*)

The unmodified critical success index (CSI) discussed in the previous section, gave equal weight to false alarm and failures to predict. Donaldson et al,[7] described a modification to the CSI using the rationale for catastrophic events in which more false alarms would be tolerable than failures to detect. Limits were placed on this, however, because too many false alarms would inevitably result in an invalid or ignored system. They recommended a significance modulus of 10 (Figure 2) for life-threatening storms, for example, a tornado. Severe cases of SWS can also be considered life-threatening events, therefore, a modulus value of 10 was applied and modified CSI* values were calculated for each test.

The resulting values of CSI* for the extrapolation tests are seen in Tables 12a and 12b. Values have risen, as expected, and are more even overall. The drop in magnitude between the 0 and 15-min forecasts has lessened, Table 12a. The most noticeable improvement has occurred in the differentiation of higher threshold SWS values, Table 12b. The surface systems, tests 5 and 6, show no improvement whatsoever. At both thresholds, the CSI*'s of the 15-m tower systems are equivalent to the CSI*'s of the 30-m tower systems.

In the screening regression tests, Tables 13a and 13b, values of CSI* for the low threshold have increased from the low seventies to the low eighties. Little distinction, however, can be made between the screening regression options. The surface system, test 7, is as good as the 30-m tower system, test 1. In comparison with the CSI* values of the extrapolation tests, Tables 12a and 12b, the screening regression values at the lower threshold, Table 13a, are higher at all times. However, at the higher threshold, Table 13b, the screening regression CSI* is lower than extrapolation at time zero.

7. CONCLUSIONS

An extensive array of towers operating at the AFGL Otis Weather Test Facility provided the basis for a detailed investigation of slant wind shear (SWS), an extremely important problem for aircraft operations. Two basic techniques were used to investigate the usefulness of offset tower wind measurements to specify and predict SWS over the landing or approach zone of a runway at intervals of 0, 5, 10, 15, 30 and 60 minutes. The techniques were extrapolation and stepwise screening regression. Two data sets were used to perform the study. A dependent set of approximately 45,000 observations over 38 days was used to select rank-ordered predictions and determine screening regression coefficients. The dependent data set was also used to produce the extrapolation constants needed to extend the data from 15-m and 30-m heights to the desired 60-m height. A smaller independent data set of 4200 observations was used for evaluation of the techniques.

Table 12. Values of the Modified Critical Success Index (CSI*) for the Prediction of SWS Speed Using the Extrapolation Technique. CSI* values are percentages. Thresholds are for (a) 4 m sec^{-1}/60 m and (b) 8 m sec^{-1}/60 m

a. SWS Speed Threshold (4 m sec^{-1}/60 m)

	Test	Forecast (minutes)					
		0	5	10	15	30	60
1	K_1 P30 - X	82	76	75	75	74	73
2	K_1 Q30 - X	71	61	62	63	62	61
3	K_2 P15 - X	77	69	69	69	68	68
4	K_2 Q15 - X	76	68	67	68	67	68
5	A3 - X	7	7	8	8	8	8
6	Q3 - X	7	8	7	8	7	8

b. SWS Speed Threshold (8 m sec^{-1}/60 m)

	Test	Forecast (minutes)					
		0	5	10	15	30	60
1	K_1 P30 - X	46	23	27	30	31	25
2	K_1 Q30 - X	29	20	16	21	22	20
3	K_2 P15 - X	43	24	27	32	27	25
4	K_2 Q15 - X	36	23	22	23	30	23
5	A3 - X	1	0	1	0	0	0
6	Q3 - X	1	0	1	0	0	0

A variety of evaluation criteria were used to compare the two techniques. Correlation coefficients showed the near equivalence of the two techniques in specification at zero-time lag. At prediction times of 5 min and greater, however, the screening regression technique did not experience as much of a decrease in correlation coefficients as did the extrapolation technique.

The screening regression technique also minimized the root-mean-square errors of SWS and the RMSE's were more nearly equal over the full forecast interval. Two points were noted in the extrapolation tests, however. The 15-m tower errors were almost the same as the 30-m tower and the surface test displayed the largest error.

Table 13. Values of Modified Critical Success Index (CSI*) for the Prediction of SWS Speed Using the Screening Regression Technique. CSI* values are percentages. Thresholds are for (a) 4 m sec^{-1}/60 m and (b) 8 m sec^{-1}/60 m

a. SWS Speed Threshold (4 m sec^{-1}/60 m)

	Test	Forecast (minutes)					
		0	5	10	15	30	60
1	P30, Q30	86	85	85	84	84	82
2	P30	82	84	82	83	82	81
3	Q30	83	84	83	83	82	83
4	P15, Q15	82	82	82	83	81	81
5	P15	80	81	81	81	80	80
6	Q15	82	82	82	82	81	81
7	Surface	87	88	88	87	87	87

b. SWS Speed Threshold (8 m sec^{-1}/60 m)

	Test	Forecast (minutes)					
		0	5	10	15	30	60
1	P30, Q30	40	30	26	35	34	35
2	P30	35	26	26	29	26	26
3	Q30	25	29	26	34	34	35
4	P15, Q15	31	25	21	30	27	25
5	P15	27	23	21	30	25	27
6	Q15	24	28	25	31	27	30
7	Surface	32	42	37	40	39	39

In testing the two techniques for probability of detection (POD), screening regression was superior to extrapolation in the low threshold test. At the high threshold test, however, extrapolation was clearly superior to screening at time zero. At later times, 5 min to 60 min, however, the two systems produced nearly equivalent POD's. Within the extrapolation tests, the 15-m POD's were equivalent to the 30-m POD's at both thresholds. The surface extrapolation system, Tests 5 and 6, were completely ineffective in detecting SWS. On the other hand, the screening regression system tests showed very little variation with one another.

False alarm ratios (FAR) for the two techniques showed the equivalence of the two at zero time lag for the low threshold. For prediction greater than or equal to 5 min the extrapolation FAR increased while the screening regression FAR remained almost constant. At the high threshold, the FAR increased considerably for extrapolation but remained somewhat lower for screening regression.

The critical success index (CSI)*, modified to allow for a higher rate of false alarms in predicting life threatening situations, showed that the screening regression technique achieved a higher, more nearly uniform, score over the full range of forecasts than the extrapolation technique for discrimination at a low threshold of SWS. In addition, the screening regression tests showed little variation on intercomparison.

A different result, however, was obtained at a higher level of SWS discrimination. At this level, the extrapolation technique CSI*'s of the 15-m and 30-m offset tower systems were nearly equal to each other throughout the forecast range and were better than the screening regression tests at time zero. The screening regression technique, however, yielded higher values of CSI* for forecasts of 5 min and beyond. Intercomparison of the screening regression tests showed that the multiple tower system gave a higher CSI* at time zero but that the surface system alone gave higher CSI*'s for forecasts of 5 min and greater.

In summary, there are a few distinct points that should be made. First, both the independent and dependent data bases occurred during the spring of 1981. During this period no thunderstorms were reported to have occurred, therefore gust fronts and downbursts were not a part of the data base, yet a significant number of strong SWS events occurred. Second, the surface-based wind system without the benefit of extrapolation or screening regression was of little value in specifying or predicting SWS. Third, the screening regression equations must be judged, overall, to be superior to the extrapolation technique in predicting SWS speeds. Last, and of great interest is the fact that the surface-based wind data utilized with the screening regression technique achieved higher scores on the Probability of Detection (POD) and the weighted Critical Success Index (CSI*) than all of the tower systems in the forecast range between 5 and 60 minutes.

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